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Mr. David M. Gibbon

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Surrey Satellite Technology, Ltd.
Surrey Space Center
University of Surrey
Guildford, Surrey GU2 7XH
United Kingdom

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ABSTRACT (Maximum 200 words)

This report results from a contract tasking Surrey Satellite Technology, Ltd., as follows: The Grantee will investigate the performance trade-offs for micro-satellite propulsion between a next-generation resistojet using xenon propellant and carbon heaters, and other methods. These include existing resistojets and micro-pulsed plasma thrusters. Development and testing of carbon monolith heaters and a prototype thruster will be performed. Pressure and temperature of the gas in stagnation chamber will be measured. Specific impulse and thrust will be measured if the facility at ESTEC is available: otherwise it will be estimated based on mass flow.

14. SUBJECT TERMS

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SATELLITE TECHNOLOGY LTD

Carbon resistojet Phase 2 report
(analysis & testing)

AUTHOR

Adam Baker

REFERENCE

SPEZ-73651-01

DATE

15/09/2004

PROJECT

SP : CARBON RESISTOJET EOARD

REVISION

01

PREPARED BY	
Name: Sanjay Mistry	
Title: Propulsion Engineer	Signed..
CHECKED	
Name: Dr. Adam M. Baker	
Title: Senior Propulsion Engineer	Signed .
APPROVED	
Name: David Gibbon	
Title: Team leader - Propulsion	Signed... ...
CUSTOMER APPROVAL	
Name:	
Title:	Signed..

Surrey Satellite Technology Limited,
Surrey Space Centre,
University of Surrey,
Guildford,
Surrey,
GU2 7XH, UK

Tel: +44 1483 683474
Fax: +44 1483 689503

email: a.baker@sstl.co.uk

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1 GENERAL

1.1 Introduction

The objective of this research is to examine the feasibility of using a novel, amorphous (glassy) carbon material manufactured by MAST Carbon as a high efficiency heat exchanger to improve the performance of an SSTL low power resistojet. The first part of this research, detailed in the interim report 'EOARD Carbon resistojet: Phase 1 Report', SSTL reference SPEZ-54456-01, AD-01, included:

1) A overview of the monolith properties, its fabrication process and data from tests conducted at MAST with a on optimised monolith and inert Argon propellant.

2) A summary of the estimated the potential performance of a resistojet using Xenon propellant and an optimised MAST Carbon monolith.

3) A comparison between the low power resistojet as currently used by SSTL for microsatellite orbit modification, and pulsed plasma thrusters.

This Phase 2 report covers further research, including:

a) Consideration of methods of coupling power into carbon monoliths for propellant heating.

b) An evaluation of the efficiency of heat transfer from a carbon monolith sample to nitrogen propellant (xenon is planned)

1.2 Scope

The work to be carried out under this contract is broken down into the following work packages. WP1 was covered in the interim report, AD-01. Results from the remaining Work Packages are summarised in the final contract report.

WP1) Summary of the potential of using carbon monolith heating elements for propellant heating in a low power resistojet, including the expected performance benefits. Comparison of micro pulsed plasma thruster (μ-PPT) technology, of interest to AFRL, to low power resistojets as built and flown in space by SSTL.

WP2) Quantification of the efficiency of carbon monolith heating of propellant flow, using an optimised (in terms of structure, composition and resistivity) sample provided by MAST. This set of tests will be performed in a laboratory situation, and will also address the issue of coupling electrical power into the carbon heat exchanger monolith. This latter problem will also be considered prior to contract start under internal (SSTL) R&D funding.

WP3) Design and fabrication of a prototype thruster, based on the existing low power resistojet modified to accept a carbon monolith heater. The thruster will be instrumented to measure key parameters such as chamber pressure and gas temperature.

WP4) Testing of the carbon monolith heated thruster in the SSTL laboratory using initially nitrogen and subsequently xenon propellants. Estimation of the specific impulse from mass flow data, for comparison with previous laboratory tests on the DMC low power resistojet thrusters.

An optional item is WP5, which will entail further testing at ESA's ESTEC research centre using a high accuracy load cell to accurately calculate overall thruster performance in terms of electrical power efficiency and specific impulse. Previous tests of an SSTL low power resistojet with Xe propellant at ESTEC are detailed in [AD-02] and [AD-03]. WP5 was earlier stated to as being dependent on the availability of facilities and support staff at ESTEC, with an alternative option being to use a planned vacuum operation millinewton range thrust balance under development at SSTL. The ESTEC facilities were unavailable at the time of writing this report, and the SSTL millinewton load cell was being calibrated. It is proposed to carry out this work package and additional work (see later) under internal SSTL R&D funds and to provide an additional report to EOARD at a later date

WP6) Analysis of the data and summary in a research report for EOARD.

The Phase 1 report recommended the following investigations:

1) An optimised carbon monolith sized for a typical SSTL low power resistojet was requested by MAST. This monolith was requested to be processed at >1000°C to enable operation at up to 800°C (the processing temperature to be higher than the operating temperature by reasonable margin to ensure no long term structural changes during operation and cycling). The resistivity and hence resistance of the monolith at 1000°C will be tailored, by processing and if necessary doping the carbon to match the power / current capability of the selected power supply at SSTL. A high current power supply will be required since the monolith processed at high temperature will have a low resistivity; a supply rated at up to 40A is available at SSTL's Propulsion Group Westcott test site.

2) A further request for optimisation, based on the initial MAST findings summarised in [AD-01] was to modify the monolith cross section scale, making the carbon walls thinner and increasing channel area for a given overall cross section. This should increase the efficiency of heat transfer to the propellant gas. MAST have provided a modified monolith which was tested at SSTL

3) SSTL will design and fabricate a carbon monolith container, essentially a low power resistojet chamber and nozzle suitable for operation at up to 1000°C with appropriate electrical connections for the heat exchanger medium.

4) Performance mapping tests will be performed.

1.3 Reference documents *(not under the control of SSTL)*

Reference Documents identified in the following text are identified by **RD-n**, where "n" indicates the actual document, from the following list:

RD-01	"Fundamentals of Classic thermodynamics",	Van Wylen & Sonntag, edition 2e, page 684
RD-02	NIST Chemistry WebBook	http://webbook.nist.gov/
RD-03	Quest Consultants Interactive Enthalpy-Pressure diagram	http://www.questconsult.com/~jrm/enthpres.html; page last updated 10/7/2001; accessed 15/4/2003.
RD-04	Handbook of chemistry and physics	Lide D R (ed.); *CRC* Press; 76th edition 1995-1996; p. 6-20.

1.4 Applicable documents

Applicable Documents identified in the following text are identified by **AD-n**, where "n" indicates the actual document, from the following list:

AD-01	SPEZ-54456-02	EOARD Carbon Resistojet: Phase 1 Report
AD-02	R3PA-49107-01	Test results (N_2) – low power resistojet, 30W thruster
AD-03	R3PA-43219-01	Test results (Xe) – low power resistojet, 100W thruster
AD-04	DNGA-30303-01	DMC Resistojet Thruster - Performance Analysis Report

1.5 Acronyms & Abbreviations

DMC	Disaster Monitoring Constellation
Isp	Specific Impulse
SSTL	Surrey Satellite Technology Limited

2 CARBON MATERIAL FOR RESISTANCE HEATING

2.1 Current resistojet and requirements for the new design

The SSTL low power resistojet is consists of a brazed stainless steel tube and expansion nozzle containing two tightly wound nichrome electrical resistance heaters, and is designed to both vapourise liquid butane, and heat gaseous butane, xenon and nitrogen propellants up to 600°C. An image of the AlSAT flight thruster and cutaway views of the 3D CAD model are shown below in figures 2.1. and 2.2.:

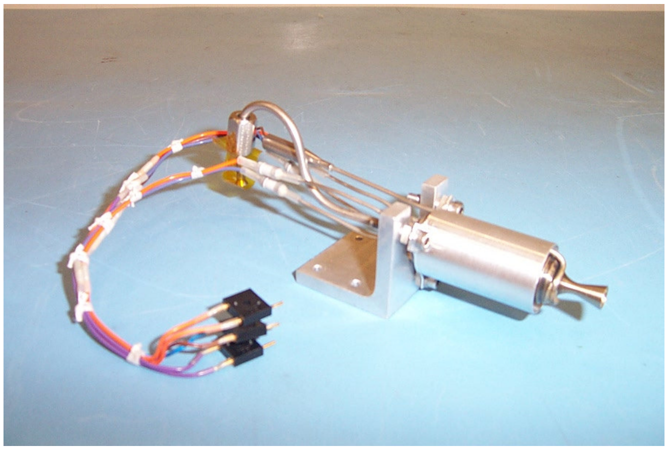


Figure 2.1: AlSAT-1 flight thruster on support bracket (thruster encircled by aluminium radiation shield)

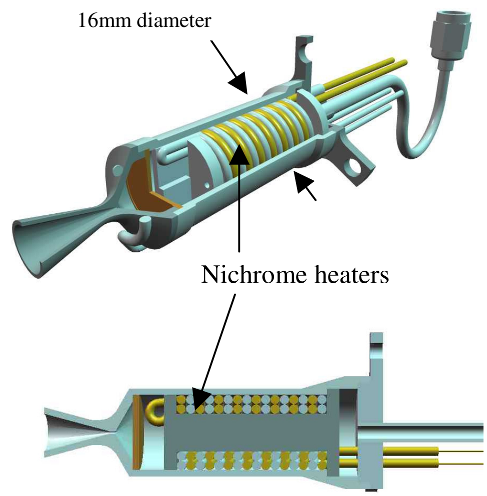


Figure 2.2: Cutaway views of 3D solid model

The technical specification for the current low power resistojet, henceforth referred to as the 'resistojet' is shown below in table 2.1. The performance parameters shown in this table are for the operation of the resistojet with Xenon. The resistojet although capable of supporting twin 50W heaters has only been tested with heater power input of up to 65 W due to limitations on the operating temperature of the thruster case stemming from the brazing process used to seal it.

Parameter	**Value**
Voltage	28V DC (nominal)
Thruster Mass (inc bracket)	104 grams
DMC System mass	Standard DMC standard (butane propellant): 8560g, inc. 2350g propellant DMC+4 (xenon propellant): 12200 – 18500g, inc. 5670-12000g propellant
Throat diameter	0.42 mm
Area expansion ratio	208:1
Maximum operating temp	Xe: 630°C (limited by case brazing); Butane: 450°C (limited by thermal dissociation or cracking of propellant leading to nozzle coking)
Propellants (primary usage)	Butane, Xenon, Nitrogen
Materials	Thruster casing: Nickel Heaters: Ni-Cr alloy Heater leads: Nickel Heater lead insulation: woven silica glass

Heater	2 x 15 Watts	up to 2 x 50W possible
Verified Specific Impulse performance, Xenon propellant	56.3 seconds (at 9 mN thrust, 30 W electrical power input)	53.5 seconds (at 20 mN thrust, 65 W electrical power input)
Total impulse	3130 – 6735Ns	2974 – 6400Ns
Thrust	30-60mN nominal performance mapping carried out up to 90 mN	
Mass flow rate	0.05-0.1 g/sec nominal	
Operating pressure	Typically 1-4 Bar gauge	
Start-up Power Requirement	15W @ 28V for 10 minutes	<65W @ 28V for <10 min
Maximum Chamber Operating Temperature achieved	290 °C	585 °C

Table 2.1.

A thruster performance specification based on the use of Xe propellant and operation at high temperature, in excess of the ~450°C at which butane thermally dissociates, has been derived from SSTL's design of future DMC missions requiring Xe propellant and this is summarised in table 2.2. below. A new resistojet rig that accommodates the carbon monolith heating element was fabricated to attempt to realise the performance specification below. Section 3 details the experiments carried out with the resistojet rig.

Parameter	**Requirement**
Propellant	Xenon
Specific Impulse	50 seconds minimum 60 seconds target
Total impulse	2,000 N sec – Operational
Thrust	30-60mN nominal Performance mapped up to 100 mN
Mass flow rate	0.01 - 0.1 g/sec nominal
Operating pressure	Typically 1-4 Bar gauge (2-5Bar absolute). Performance mapping up to 10 bar
Start-up Power Requirement	30W max. @ 32V max. for 5 - 7 minutes
Chamber Temperature	600 °C minimum >1000 °C target
Target Delta V for 130kg enhanced microsatellite	12m/s

Table 2.2.

2.2 The new carbon heating elements and preliminary tests

2.2.1 Introduction

Low power resistojets utilising Xenon propellant need to meet the increasing deltaV and potentially attitude control requirements of future microsatellite missions. A heat exchanger is required that will heat the propellant flow to a higher

temperature more rapidly and efficiently compared to the current SSTL resistojet heater (for the same given applied power), enabling small thrust impulse bits, lower expended power and less propellant expenditure.

To develop such a heating element, SSTL partnered with MAST Carbon. MAST are experts in producing carbon and ceramic components with a wide range of geometries and properties. A range of carbon microchannel 'monoliths' have been fabricated by MAST and tested in the laboratory with Nitrogen and Argon gas.

Figure 2.3 below shows a picture typical monolithic carbon structures produced by MAST.

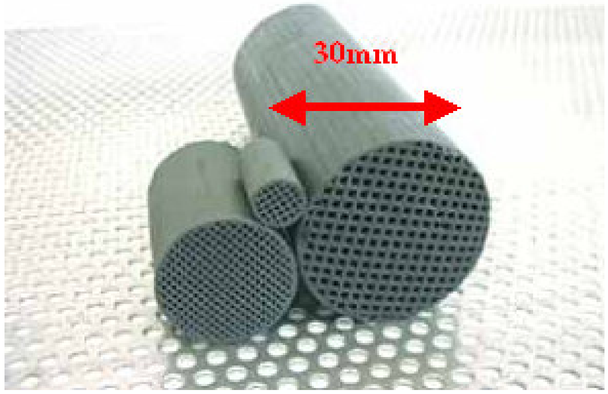


Figure 2.3.

Document AD-01 gives greater details about the following aspects of the MAST carbon heating element, including:

- Benefits of its use in the low power resistojet application
- Suggestions for connecting it to electrical circuitry
- Fabrication details

Preliminary tests were carried out on a range of carbon microchannel 'monoliths' with the aim of comparing the experimental efficiency of the carbon heating element to initial calculations and thereby characterise its potential to be used in this application. These results from the preliminary tests are described in the remainder of this section.

2.2.2 Ar flow testing at MAST and comparison with SSTL resistojet

Experiments were performed on monolith lengths of 2, 3 and 4cm and for varying monolith resistances (adjusted through the pyrolysis temperature and residence time).

Experiments were limited to a maximum of 660°C, set by the post-treatment temperature and the 30V/2A (60W) limit imposed by the power supply. For the lowest resistance monoliths (1Ω/cm), a 4cm length with a 2A current limited power supply draw would be limited to only 8V or 16W. Note that the processing temperature of the carbon monoliths can be increased to well above 1000°C, although the higher processing temperature lowers the resistance to the point where the 2A current limitation of the MAST power supply would not have allowed sufficient heating. This is a fundamental limitation of the carbon monolith, in a heat exchanger application a balance must be struck between:

1) Processing at a high temperature, allowing repeated operation at a higher temperature without microstructural degradation, but leading to low resistance and hence high current input to generate a given heating power, and
2) Processing at a lower temperature, limiting operational temperature but retaining a high resistance and thus allowing a low current to produce a high heating power.

On board a spacecraft a high current can be drawn for short periods from batteries, although the electrical power system, like many standard laboratory based power supplies is likely to be limited to low current draw.

A 3cm long monolith was heat treated at 660°C for 3 hours, increasing its resistivity. The gas temperature dropped in a non-linear fashion as flow rate increased for a given power, due to the reduced (heating) residence time. The graph below shows, for example, that at 10W input power the gas temperature fell from 280°C to 180°C when the flow rate increased by a factor of five, from 400 to 2000ml/minute. Note that MAST's initial tests were conducted using Ar gas. A flow rate range of 400 to 2000ml/minute Ar range corresponds to a Xenon flow rate of between 0.036 and 0.181g/s, due to the difference ni

molecular masses. Heat capacity also affects the comparison, although the heat adsorption being of Xe v. Ar is comparable for a given flow rate due to the almost identical heat capacities of Xe and Ar at room temperature, 300K.

MAST's subsequent tests, and the SSTL tests detailed later used nitrogen, N_2. Volume flow rates of 1-3litres (1000-3000mL) / minute in N2 correspond to a Xenon mass flow rate, based on equivalent heat adsorption capacity of 0.027 – 0.081g/s.

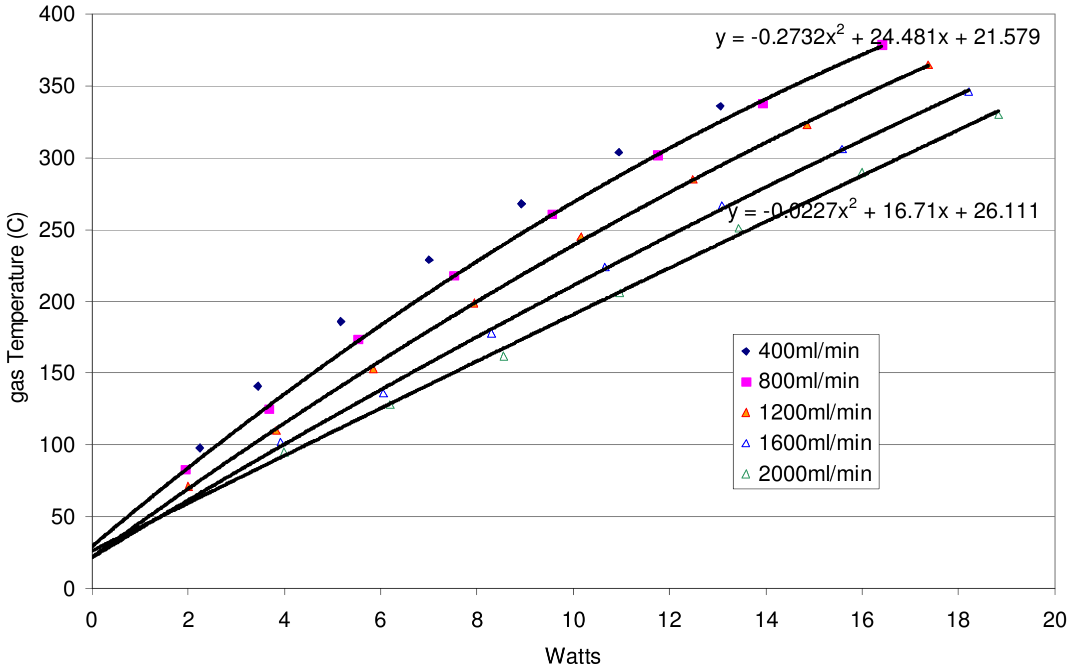


Figure 2.3: Applied power v. measured gas output temperature

MAST's experiments showed that around 15W of input power resulted in gas outlet temperatures of 275-325°C at the range of flow rates representative of the SSTL resistojet using Xenon propellant.

Extrapolation of the 2000ml/minute data also indicated that temperatures of around 600°C (comparable with the limiting temperature of the current SSTL low power resistojet) should be achievable with the target power of 30W. This could not be reached in the MAST experiments due to the current limitation imposed by the available power supply. This temperature projection was confirmed in discussions with MAST.

Figure 2.4 and Table 2.2 show data from the SSTL low power resistojet (Figure 2.1.) tested under vacuum using Xe propellant at ESTEC:

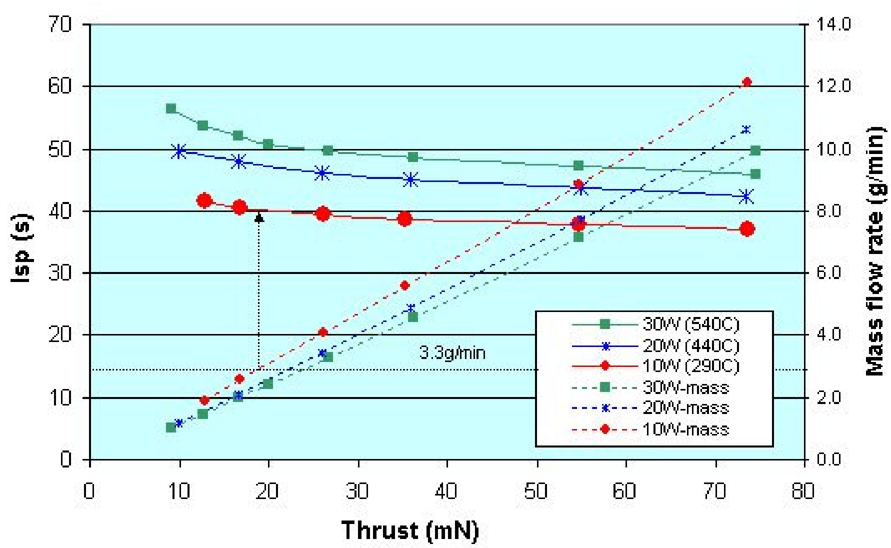


Figure 2.4: Isp achieved for low power resistojet using Xe propellant, compared with thrust and mass flow rate

Input power (W)	Thruster steady state temperature (°C)	Mass flow rate (g/min)	Thrust (mN)	Isp (s)
30	540	0.93	9.3	56.3
		9.9	74.5	46.0
20	440	1.22	9.9	49.7
		10.6	73.4	42.4
10	290	1.9	13.0	41.6
		12.1	73.6	37.1

Table 2.2

The AlSAT-1 data, shown below revealed that 30W of power raised the temperature of the resistojet to ~280°C in 5 minutes. On opening the valves to allow propellant flow, an initial rise in thermocouple temperature was recorded as thermal energy was carried by butane vapour from the heater to the thermocouple. The temperature then fell over 3 minutes to ~180°C. Laboratory tests of the resistojet have shown that the gas temperature lies within 20°C of the measured case temperature up to ~300°C.

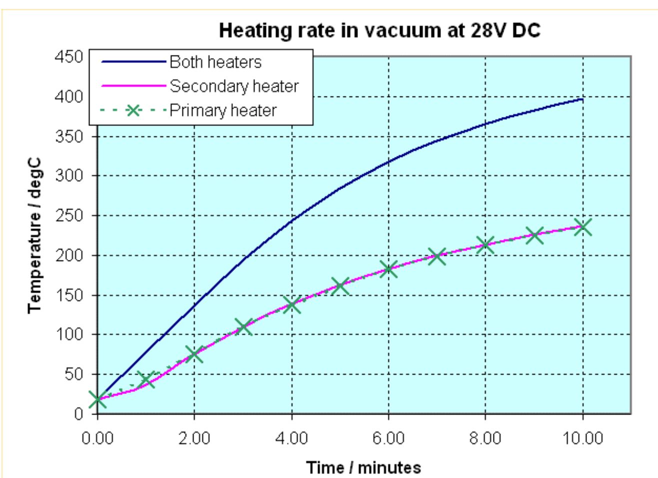


Figure 2.5: Heating rate measured on the AlSAT flight thruster, 15 and 30W input power

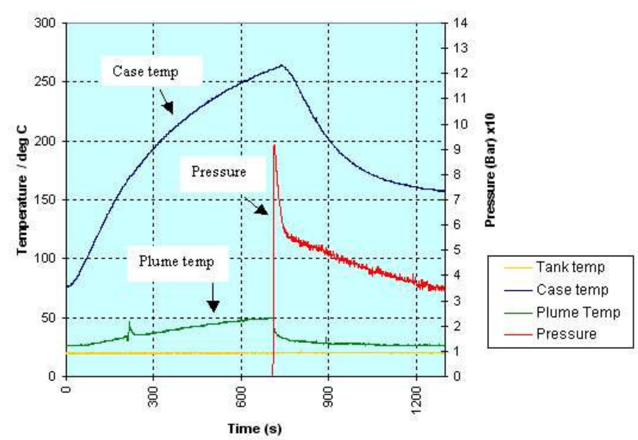


Figure 2.6: Butane flow data for AlSAT-1 fight thruster, 15W input power

In contrast, the MAST tests using Ar found that the carbon monolith heating element reached peak temperature in less than 3s after power is applied, as shown below in Figure 2.7. Nitrogen propellant flow commenced at the same time to avoid damage to the heater from thermal runaway, but took from 35-68s to reach a maximum temperature of 430°C. The gas temperature is considerably lower than the monolith or heater temperature, unlike the SSTL low power resistojet used on AlSAT-1 where the temperature were comparable. This can be taken to indicate the low thermal inertia of the test setup, such that gas which leaves the monolith cools rapidly due to surrounding material. Xenon gas however should reach a higher equilibrium temperature for a given flow rate and monolith temperature than nitrogen due to a heat capacity only 70% of nitrogen.

In an actual thrusters the thermal inertia could be increased, although this would tend to negate the benefit of the rapid heating property of the carbon monolith. An alternative would be to expel the propellant from the nozzle immediately after exiting the heater, maximising the thermal to kinetic energy conversion. This could be achieved by minimising the distance between the monolith heat exchanger and the nozzle exit plane, and reducing the nozzle heat capacity, effectively by reducing its mass and/or the heat capacity of the material.

However, it is possible that the monolith thermocouple may have been occupying one of the passages, stagnating the flow of gas and resulting in an artificially high temperature or 'hot spot' at the thermocouple location.

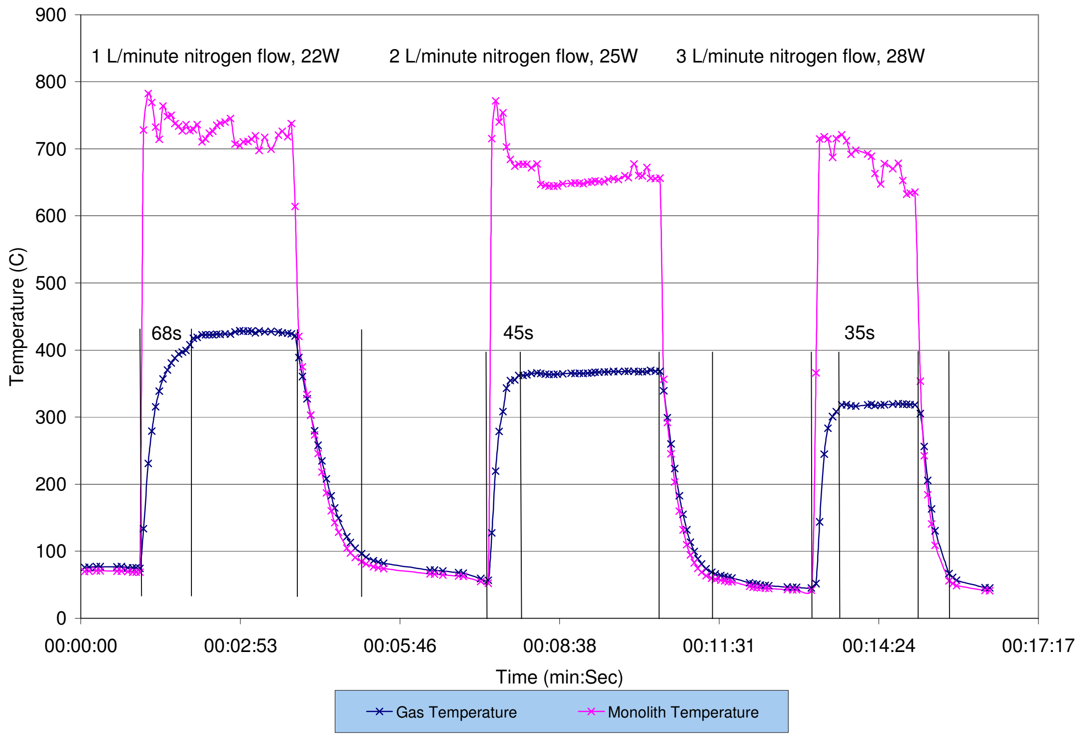


Figure 2.7: MAST carbon monolith heater data

Figure 2.7 also shows that the temperature rise time diminished as flow rate increases, this is thought to be due to reactor thermal inertia. A higher (mass) flow carries more thermal energy to the reactor, heating up the material surrounding the monolith more quickly and enabling the system to reach thermal equilibrium faster. However the equilibrium gas temperature is lower as mass flow rate increases, since the total thermal energy supplied by the heat exchanger is spread over a larger mass of gas.

The 1 litre / minute curve in Figure 2.7 is most comparable to the desired flow regime, 1litre / minute nitrogen being equivalent to 0.027g/s xenon. Tests of an SSTL low power resistojet using conventional heaters at ESTEC found that 20W of input power resulted in an equilibrium thruster temperature of 440°C, and generated a thrust of ~12mN at an Isp of 49s. In contrast, the MAST monolith test with the same equivalent gas flow showed a peak gas temperature of 430°C with 22W of input power, and a gas rise time to steady state of 68s. On this basis the carbon monolith heat exchanger appears to be competitive with the current resistojet, and exceeds its performance on rise time rapidity.

2.2.3 Conclusions from MAST testing

The conclusions as detailed in the Phase 1 report, AD-01, were:

Further optimisation of the carbon monolith was needed to improve heat transfer to the propellant gas, enabling higher gas temperatures to be reached but at a comparable power level to the maximum available to an SSTL resistojet, around 30W. This thermal absorption within the test setup, however improved heat transfer could also be achieved by changing the monolith cross section arrangement.

The output gas equilibrium temperature for a given input power was comparable to the SSTL low power resistojet, using an unoptimised monolith channel section. The rise time of the heat exchanger is far faster for the carbon monolith, although gas temperatures for xenon propellant were not directly measured for the comparable SSTL low power resistojet. A monolith cross section optimised for heat transfer is expected to outperform the SSTL low power resistojet.

However, a higher carbon monolith heat treatment temperature will be required to allow higher temperature operation. The original monolith heat treatment temperature was 620°C, dictated by the resistance required (which falls as heat treatment, and hence useage temperature rises), limiting operation to between 300 and 400°C.

The long term stability of the carbon monolith material after several heating / gas flow / cooling cycles has yet to be established. One possible target might be 500minutes of propellant flow time at temperature, equating to 168 × 3 minute operating cycles at 30W input power, derived from the AlSAT-1 mission operational experience.

3 TESTING AT SSTL

3.1 Test equipment and setup

Figure 3.1 below shows a schematic of the apparatus used during the experiments. A detailed schematic of the resistojet thruster is shown in figure 3.2. It shows the accommodation of the carbon monolith heater, locations of the pressure & temperature taps and the electrical connections for power input to the heating element.

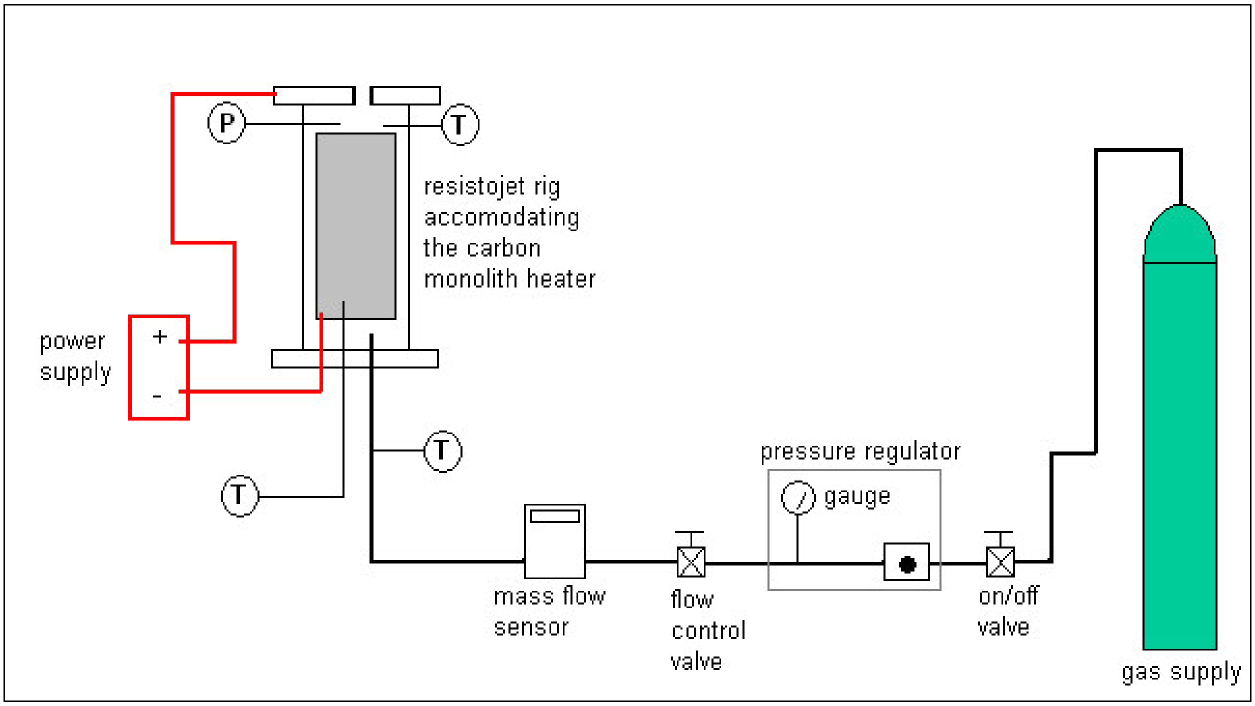


Figure 3.1. Schematic showing the test setup.

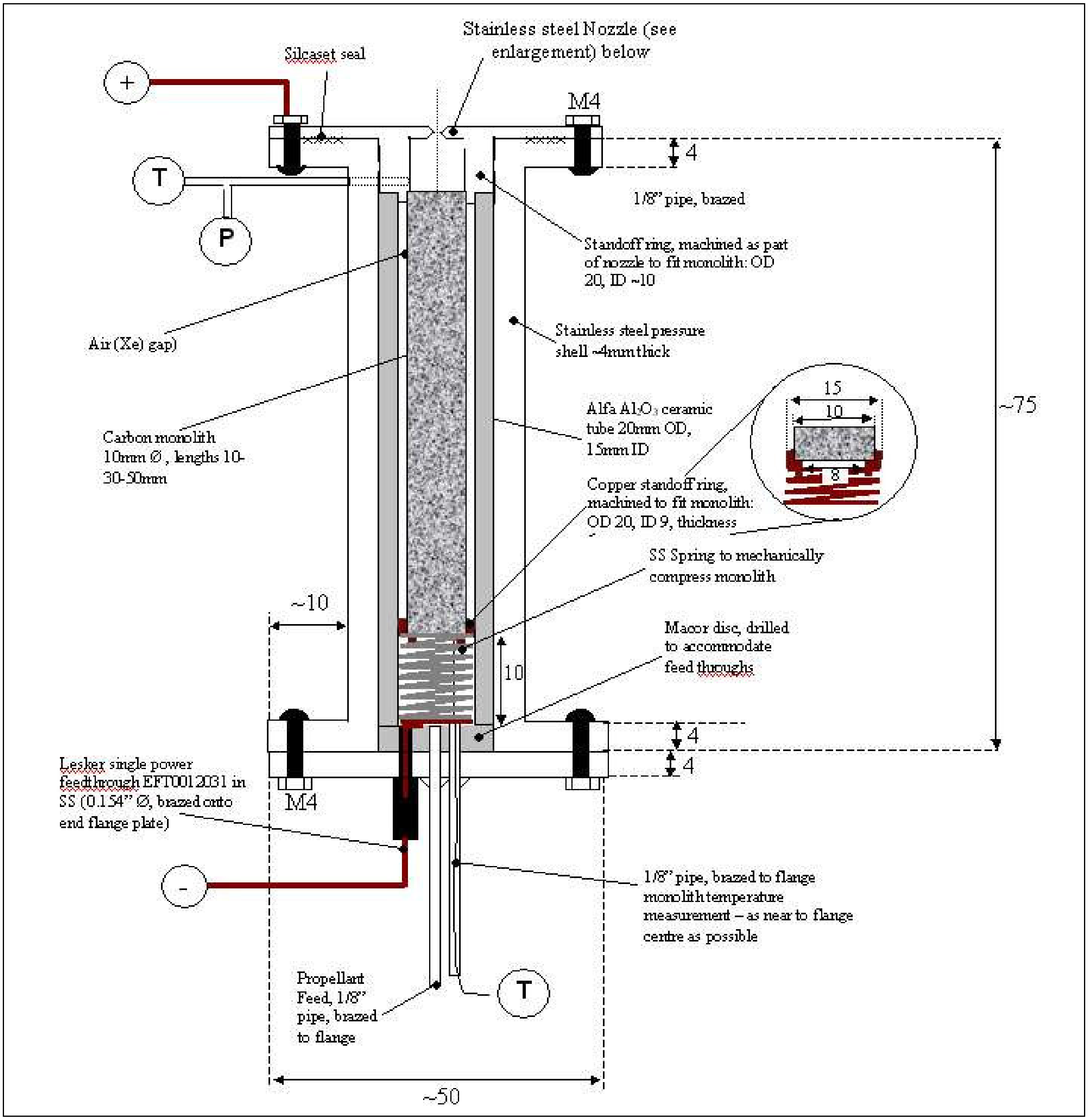
Table 3.1 below summarises further details pertaining to the test equipment used.

Item	Comments
Gas Supply	Laboratory wall mounted nitrogen supply or Xenon tank supply
Flow control valve	Standard needle valve
Mass flow sensor	0-5 Std. L/min Sensor Technics AWM5101VN
Thermocouples	K-type 0.5mm diameter industrial mineral probes Farnell No. 721-8898
Pressure Transducer	0 – 10 Barg VEGA BAR 14 BAR14.X1FA1
Power supply	0-30 V (maximum current 5A)

MAST Carbon Monolith heating element	5 cm length. Processed at 800 deg C for 6hrs, to give resistance characteristics of 0.1Ω/cm.

Table 3.1. Summary of test equipment details.

The mass flow sensor, pressure transducer and thermocouples had all been calibrated and interfaced with a data acquisition computer running Labview. The voltage and current readouts on the power supply were used to gauge the electrical power input into the heating element tested.



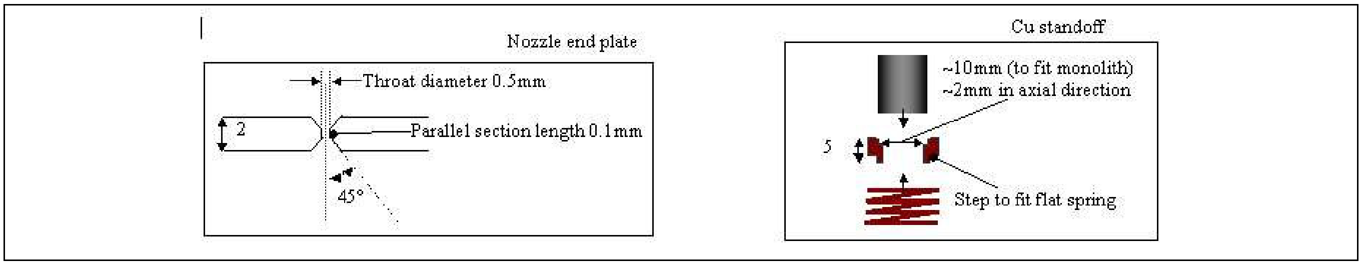


Figure 3.2. Detailed layout of the resistojet rig.

Power input to the monolith was accomplished in a similar fashion to the MAST setup detailed in [AD-01]. This used a copper standoff ring machined to be a push fit (i.e. minimal contact resistance) onto the monolith's upstream end, a push fit into a shoulder machined into the nozzle flange plate at the downstream end, with the whole assembly held in axial compression by a copper spring at the upstream end, supplied by TFC Ltd. with a flat spring cross section to minimise contact resistance.

Power was taken into the casing through a Lesker vacuum electrical feed through, the Earth return was kept as the steel casing. Thermocouples and the pressure sensor were electrically isolated from the power feed to avoid cross-talk.

Improved carbon monoliths were obtained from MAST. The improvements made were to the channel scale factor and processing temperature as follows:

- Ordinarily, decreasing monolith channel area would increase heat transfer by increasing surface area, however an analysis has shown that this does not occur as smaller channels, for a fixed overall monolith cross section reduce the Reynolds number (Re) and heat transfer efficiency falls. The net effect is that for a given total porosity in the monolith, performance (i.e. heat transfer) should be independent of channel size over quite a wide range. However by decreasing the scale factor, i.e. reducing the wall thickness for a given channel unit cell size (by changing the extrusion die used to produce the monolith), it was predicted that the heat transfer can be improved. The difference in scale factor between the old monolith and the new is shown in the image below, where the left hand monolith shows thicker carbon webs and a smaller channel cross section, the right hand (optimised) monolith shows thinner webs and a larger channel cross section, although both monoliths have similar channel unit cell sizes (although the diameters differ) :

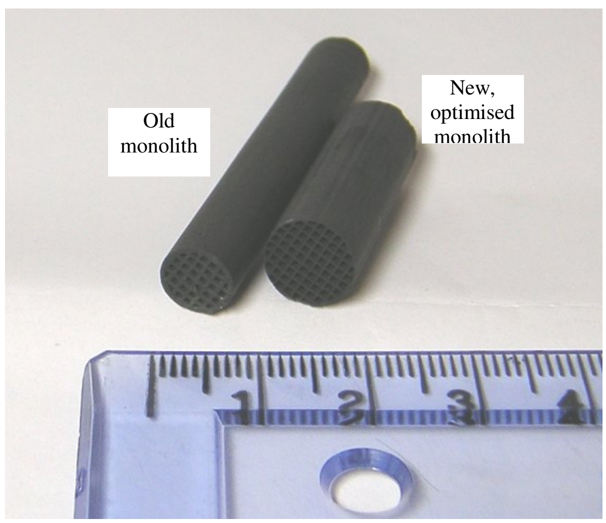


Figure 3.3 Closeup image comparing monoliths

- The processing temperature was fixed at 800°C, predicted to correspond to a resistance of 0.5-0.8Ω/cm of monolith, or 2.5-4Ω for a 50mm long monolith. 800°C processing would allow operation at up to 600°C, comparable with the upper temperature limit of the current SSTL low power resistojet. MAST could not guarantee that higher processing temperatures, e.g. to allow operation at 800-1000°C, would result in a carbon monolith with sufficient resistance to be useful without a very high current. A supplied current of 9A was estimated as flowing for a spacecraft 28V DC power supply across a 3Ω resistance monolith, which would give a heating power of >240W if uncontrolled. A 10A power supply was felt to be sufficient for further testing. However the monolith supplied by MAST, 10mm diameter and having been heat treated for 3 hours in nitrogen at 800°C had a resistance of 0.1Ω/cm, or 0.5Ω total.

The assembled test rig and thruster parts are shown in Figures 3.4-3.7, below:

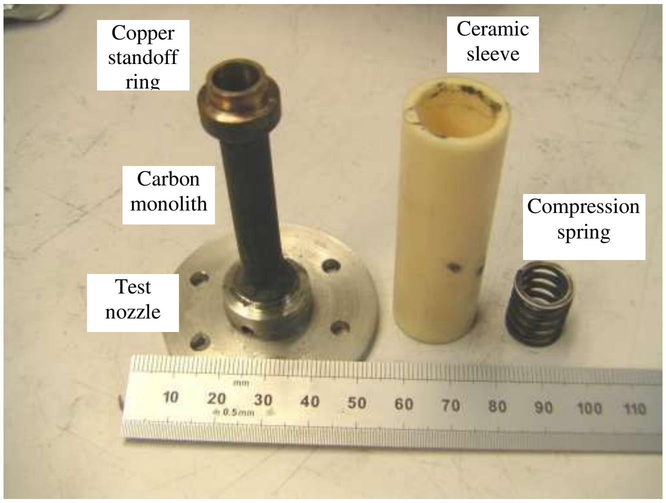


Figure 3.4. Resistojet thruster parts, dissassembled

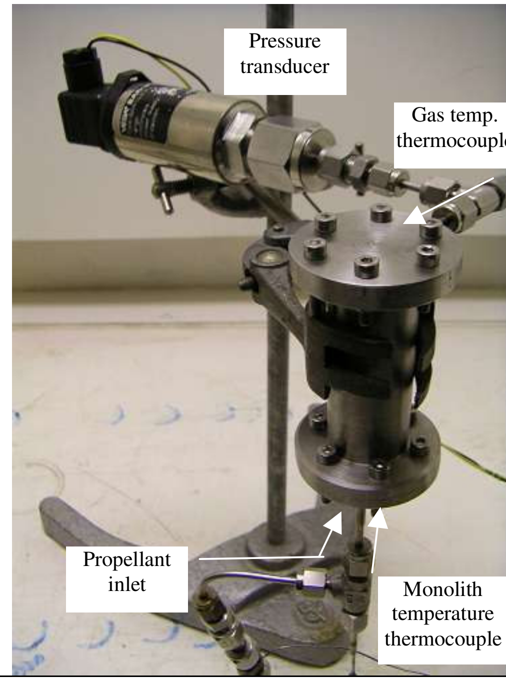


Figure 3.5. Resistojet test rig

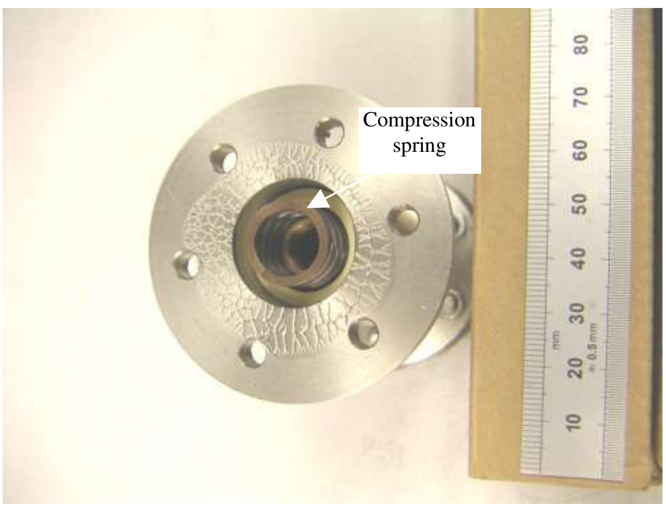


Figure 3.6. Resistojet upstream end, part assembled, showing sealant on flange plate

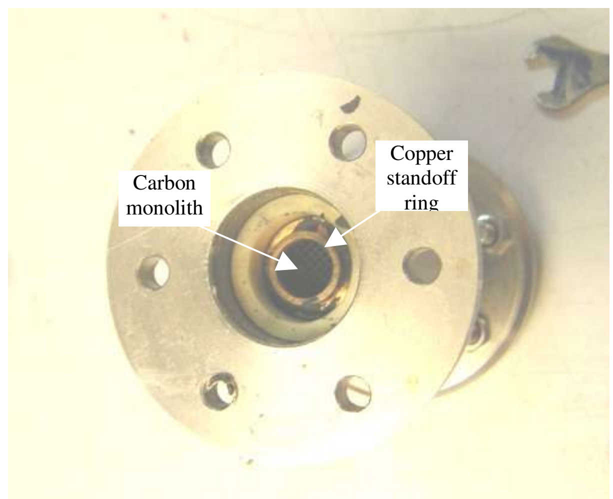


Figure 3.7. Resistojet upstream end, part assembled, showing monolith position

3.2. Test plan

The tests briefly focussed on carefully powering the carbon monolith heater up to a steady temperature with a nominal gas flow passing through the resistojet rig. This was done to gain familiarity with operation of the heating element, and, to make observations on heat up time and the extent of achievable temperatures.

Following power up checks, a logical sequence of tests was carried out to make observations and measure the relevant data required to carry out an analysis into the performance figures of merit that characterise the functioning of the resistojet. These tests involved variation of the following parameters:

- Gas flow rate (0-5 Std L/min at up to 3 bar line pressures) (limited by operating range of flow sensor)
- Monolith temperature (power input variation through alteration of current through the monolith, controlled by applied voltage across the thruster)

Using these tests, it was possible to analyse the transient and steady state performance of the heating element.

The bulk of the testing was carried out using nitrogen gas so that the entire operating envelope of the heating element could be characterised effectively. Using these results, favourable operating points for the heating element were determined in order for operation with Xenon gas to be investigated.

All tests were carried out using a 50mm long carbon monolith heating element that had a resistance of 0.1 Ω/cm.

3.3. Data Processing

The raw data logged during the experiments was processed using the equations described below. The data processing assumes idealised performance with the inclusion of a nozzle optimised to expand the in-chamber gas to in-flight ambient pressures. This assumption allowed the characterisation of the resistojet rig's performance using the thermodynamic properties of the gas measured in the resistojet rig chamber. The actual nozzle, as shown in Figure 3.2 had a short parallel section, 0.1mm long and 0.5mm diameter, and converging and diverging sections with a 45° cone angle and was not expected to offer a optimised thrust coefficient.

3.3.1 Specific heat capacity

Initially the specific heat capacity (at constant pressure) C_p of the gas is obtained. For nitrogen, it was obtained using the following expression:

$$C_p = 39.06 - 512.79\theta^{-1.5} + 1072.7\theta^{-2} - 820.40\theta^{-3} \qquad \text{(kJ / kmol K)} \qquad \text{[RD-01]}$$

For Xenon, an average value of C_p for the range of temperatures concerned was obtained from the NIST website [RD-02].

Where

C_p is the specific heat capacity (convert into units of kJ / kg K by dividing above value by molar mass of nitrogen which is 28 kg/kmol)

θ = Gas chamber temperature T_c (in K) / 100

3.3.2 Gamma

The ratio of specific heats or adiabatic index γ is calculated by

$$\gamma = C_p / (C_p - R)$$

Where

R = gas constant of the gas in kJ / kg K

(0.29694 kJ / kg K for nitrogen and 0.06347 kJ / kg K for Xenon)

3.3.3. Characteristic Velocity

The characteristic velocity C* is given by either

$$C^* = \frac{\sqrt{\gamma R T_c}}{\gamma \left(\frac{2}{\gamma + 1} \right)^{\gamma+1 / 2\gamma - 2}}$$

Where

T_c = gas chamber temperature in degrees K

Or

$$C^* = \frac{P_c A_t}{\dot{m}}$$

Where

P_c = Chamber pressure in Nm^{-2}

A_t = Throat diameter in m

m• = Mass flow rate in kgs^{-1}

The former relationship is used to make a theoretical estimate of c* performance, the latter can be used to calculate c* from measurements on an actual thruster.

3.3.4. Isp

The ideal Isp is given by

$$Isp = \frac{C^*}{g}\gamma\left[\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{1/2}$$

Where

g = acceleration due to gravity in ms^{-2}

3.3.5. Thrust

The ideal thrust F is given by is given by

$$F = Isp \cdot \dot{m}g$$

3.3.6. Energy Efficiency

For idealised thruster performance with an idealised nozzle, there are no pressure thrust effects and the useful power output is solely due to the kinetic energy expended per unit time in the exhaust jet.

$$P_{output} = \frac{1}{2}\dot{m}C^2$$

The input power to the thrusters is the sum of the electrical input power and the inlet gas enthalpy.

$$P_{input} = P_{electric} + \dot{m}H$$

Thruster electrical efficiency η is estimated as the ratio of the useful power output, to the input.

$$\eta = \frac{\dot{m}C^2}{2\left(P_{input} + \dot{m}H\right)} \qquad (3.3.6.)$$

where C is the gas velocity in metres / second.

Note also that the idealised thrust is,

$$F = \dot{m}C \qquad (3.3.7.)$$

Now from equations 3.3.5. and 3.3.7. the effective exhaust velocity for this idealised case is,

$$C = Isp \cdot g \qquad (3.3.8.)$$

Combining equations (3.3.6.) and (3.3.8), the expression for thruster efficiency (η) is now,

$$\eta = \frac{\dot{m}\left(Isp \cdot g\right)^2}{2\left(P_{input} + \dot{m}H\right)}$$

Where

P_{output} = Useful output power in W

P_{input} = Total input power in W

$P_{electric}$ = Electrical input power in W

H = Gas enthalpy at room temperature in J/kg

For Xenon, gas enthalpy has been estimated at 48kJ/kg at between 1 and 5Bar pressure and at 300K [RD-03]. For Nitrogen, gas enthalpy is estimated at 8.7kJ/mol or 310kJ/kg between 1 and 10Bar pressure and at 300K [RD-04].

4. RESULTS FROM EXPERIMENTS BY SSTL

4.1. Preliminary tests with Nitrogen gas

Preliminary testing consisted of passing a flow of nitrogen through the resistojet rig whilst powering the monolith. Test data was logged for combinations of mass flow rate (ranging from 0 to 0.11g/s) and current input (up to 2.5A or 5A). During these tests the thermocouple sensing the monolith temperature always reported a temperature that was significantly lower than the gas temperature at monolith exit. In contrast the MAST results, Figure 2.7, showed the reverse. This was deemed due to an unsatisfactory positioning of the monolith thermocouple end, at the upstream (propellant inlet) end of the monolith, whereas MAST positioned theirs at the downstream (outlet) end.

Figures 4.1. and 4.2. show plots of chamber temperature against time for each test case described above. These plots were used to work out the maximum gas (chamber) temperature attainable in each case and the time taken by the resistojet rig to reach a steady or thermal equilibrium condition.

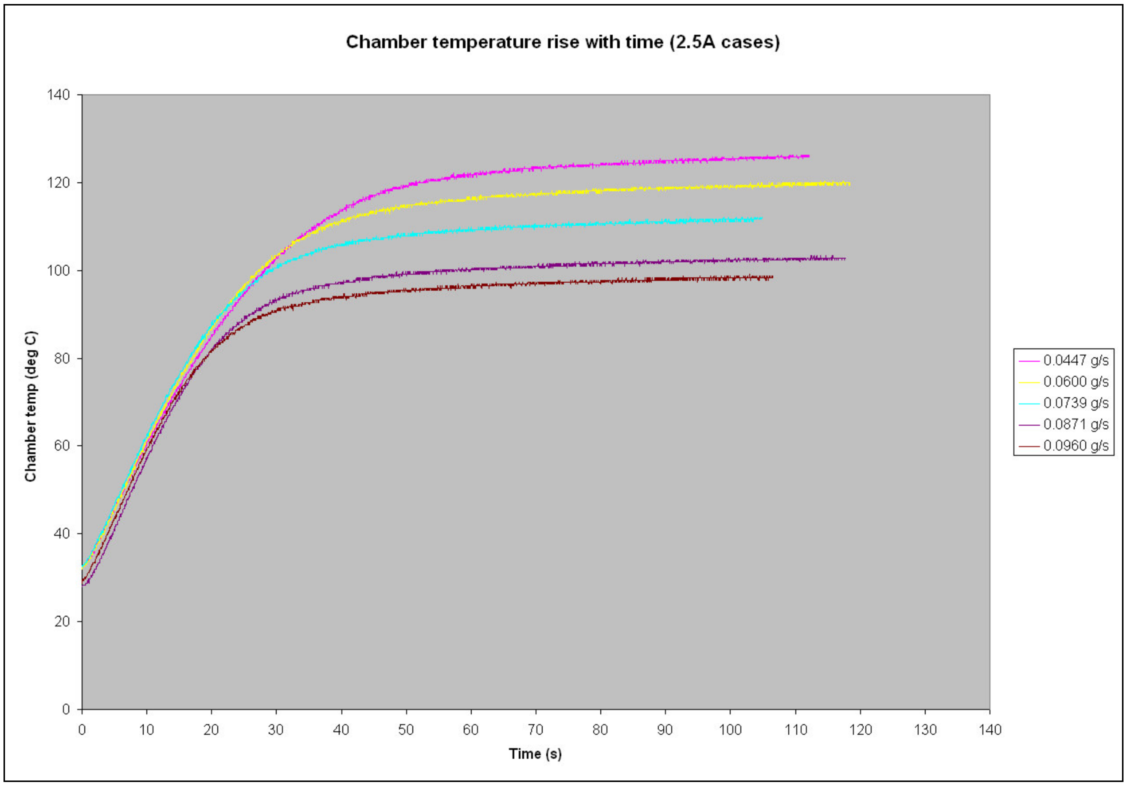


Figure 4.1. Plot of chamber temperature against time for the 2.5 A test cases.

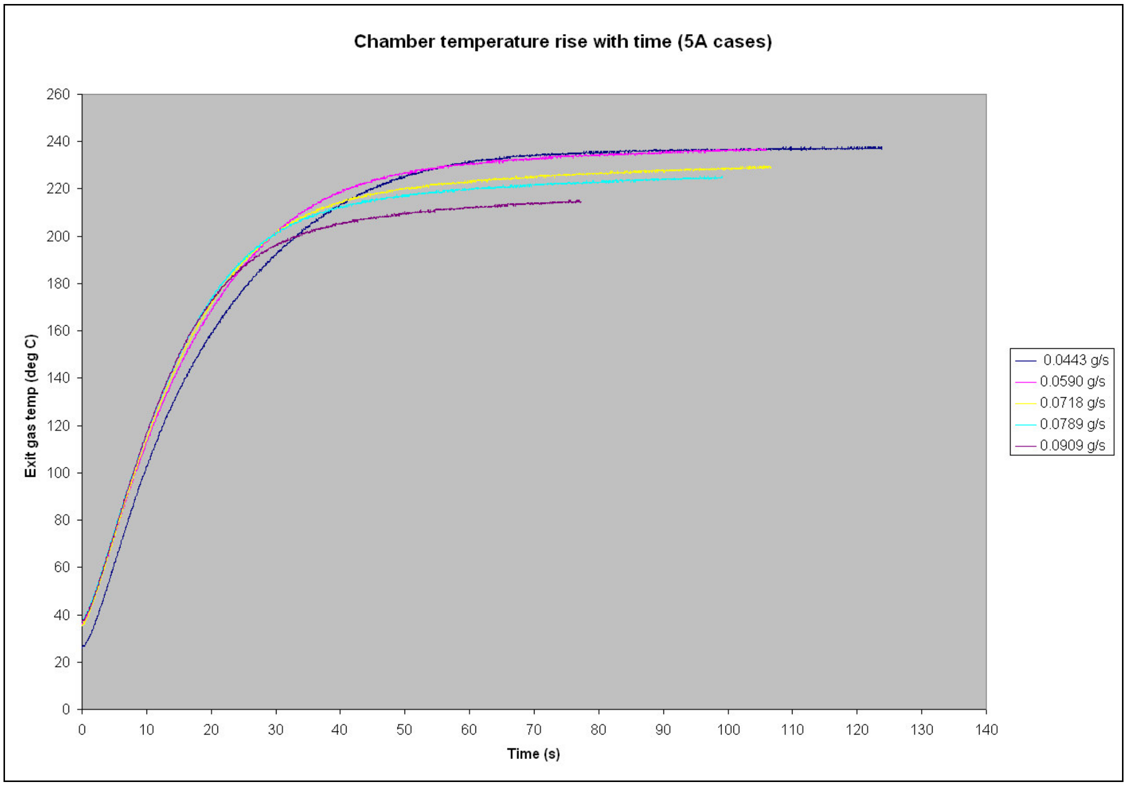


Figure 4.2. Plot of chamber temperature against time for the 5 A test cases.

Table 4.1. shows the electrical input into the resistojet rig and the maximum gas temperatures & pressures (at monolith exit or chamber) attained for the different flow rates investigated.

Electrical power input to the resistojet rig (W)	Current (A)	Voltage (V)	Mass flow rate of nitrogen (g/s)	Maximum gas temperature achieved at monolith exit chamber (deg C)	Chamber pressure (bar) (gauge)
16.25	2.5	6.5	0.0447	125	0.46
			0.06	118	0.79
			0.0739	110	1.11
			0.0871	102	1.45
			0.096	97	1.70
42.50	5	8.5	0.0443	237	0.56
			0.059	234	0.92
			0.0718	228	1.30
			0.0789	222	1.50
			0.0909	214	1.86

Table 4.1. Steady state condition data gathered from initial resistojet rig tests with nitrogen.

The thermal equilibrium condition for the resistojet rig that was used in this analysis was the instant at which the gas temperature in the chamber reached 95% of the maximum value recorded during the test case. Figure 4.3. below displays the times to reach thermal equilibrium for each test case.

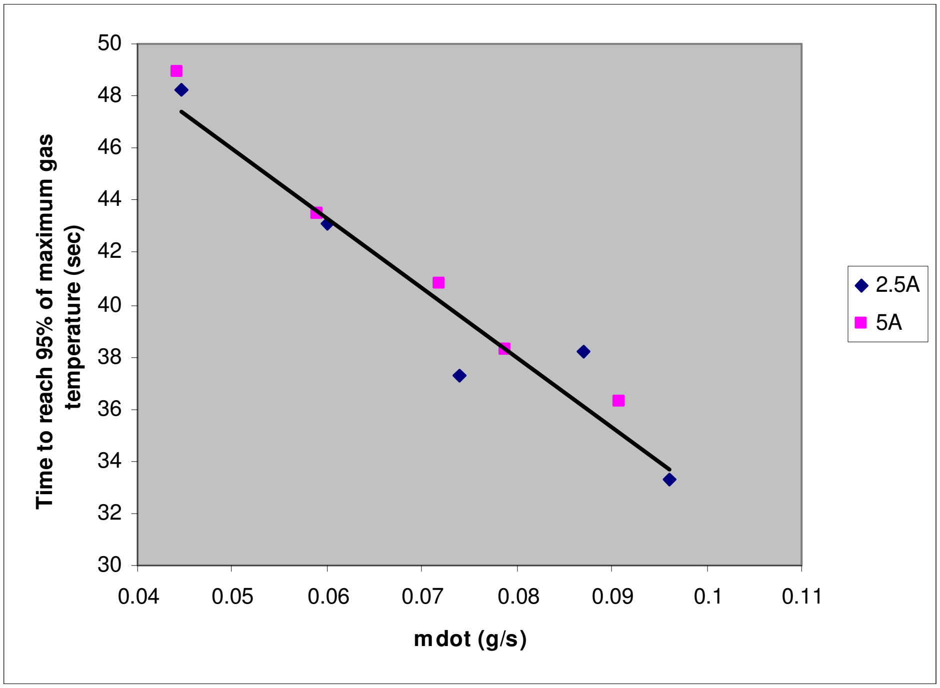


Figure 4.3. Time to reach thermal equilibrium in each test case.

The key observations and deductions from these tests were:

- Figure 4.3. illustrates that the time to reach thermal equilibrium is similar for the same given mass flow rate of gas through the resistojet rig, regardless of the electrical input power (controlled by current flow) to the heater.
- The heating element only had a resistance of 0.5 Ω and with currents of 2.5 & 5A passing through it, the maximum heat powers that it could supply to the gas were 3 W and 12.5 W respectively (because $P = I^2R$). However, voltages of 6.5 & 8.5 Volts had to be applied across the resistojet rig to enable the currents of 2.5 and 5 Amperes to be passed through the heating element. So electrical inputs of 16 and 43 Watts were being used to power the resistojet rig in the respective cases. It was thought that the remainder of the electrical circuit (presumably the electrical contacts at either end of the heating element) had an undesirably high resistance thus showing a low electrical efficiency in electric power delivery for this arrangement. The resistance of the current path through the casing and monolith combined was measured as ~3.8Ω, indicating the majority of the voltage drop, resistance, and heating was occurring at points in the casing. It should be noted that the MAST tests used an entirely ceramic chamber, with the current path passing only copper springs and standoff rings to the monolith with no steel chamber. MAST tests also used a much higher resistance monolith (processed at a lower temperature, ~640°C), around 4Ω or 8× that of the one supplied to SSTL. This would enable 64× the heating power to be dissipated for the same circuit input power, which would more than compensate for the lower heat transfer efficiency through the thicker channel wall monolith tested and reported on [AD-01]
- Doubling the current through the carbon monolith heating element doubled the maximum steady temperature of the gas in the chamber. According to the $P = I^2R$ law, the power dissipated by the monolith should have quadrupled, however, it only tripled as its resistance was reduced due to its higher operating temperature which was at the time not accurately measurable. Using this observation, it would be reasonable to assume that an input current of around 16-20 A would be required to enable the nitrogen gas temperatures to be raised to the 800 °C mark at nitrogen gas flow rates of 0.03 - 0.04g/s using the same setup. The power supply available during the time available to run the tests above was limited to 5A. It is expected that a higher current power supply will become available for subsequent testing.

4.2. Further testing

At the conclusion of the preliminary tests, attempts were made to improve the electrical efficiency of the circuit by essentially reducing the resistance of the connecting interfaces. It was hoped that this might reduce the electrical resistance of thruster casing sufficiently to ensure that the majority of the voltage drop and hence resistance heating occurred across the monolith. This was done in the following ways:

- Larger diameter copper wires were used to supply the resistojet rig with electrical power.
- Conductive graphite cement was applied as a fillet around the monolith to reduce contact resistance at the upstream stand off ring and nozzle interface, as shown in figure 3.2.
- A thick disk of soft graphite gasket material was used to enhance the connectivity between the Lesker single power feedthrough and the compression spring that formed part of the electrical circuit supplying power to the monolith.

After re-assembly of the resistojet rig with the above changes, the thermocouple measuring monolith temperature was re-postioned such that it was located approximately 3-4mm deeper relative to its position in the preliminary tests, which was estimated as just outside the monolith at the upstream end.

Initially tests with this modified setup were unsuccessful in raising the gas temperature even slightly. This was deemed to be as a result of the new thermocouple position short-circuiting the current and not allowing it to flow down the monolith and then across the stand off ring in the stainless steel nozzle. Instead it simply flowed across a small section of the monolith (up to a point at which the thermocouple touched it) and then across the resistojet rig stainless steel case due to the short circuit through the thermocouple measuring monolith temperature. This also explains the low potential difference (voltage) of 1.5 V that was observed when the 2.5 A current to be passed through the resistojet rig. At this point it is worth noting that MAST did not encounter this type of problem as their experimental setup utilised a thermocouple that was positioned at a downstream position of the monolith after the electric current that passed across the majority of the heating element, this is shown in [AD-01].

Having removed the thermocouple in question completely from the setup, the voltage required across the electrical circuit to pass the 2.5 A current, through the resistojet rig rose to 5.5 V. This voltage was 15% less than that recorded during the preliminary tests implying that the contact resistance around the monolith heating element had successfully been reduced, but this setup only yielded maximum exit gas temperatures that were half the order of those observed in the preliminary tests (around 120°C compared to 240°C before). Possible reasons for this are:

- Since the overall resistance of the heating element assembly had been reduced, it was dissipating a lesser amount of power to the gas than before, for the same circuit input power.
- The upstream copper standoff ring and downstream nozzle shoulder may have originally had a high contact resistance with the monolith, before application of the graphite cement. This may have lead to localised heating at the interfaces, the high thermal conductivity of the monolith leading to spreading of the heat throughout and good propellant heating. However it is not thought that this would represent an electrically efficient means of heating propellant, and might ultimately lead to monolith failure after repeated high temperature cycles at these points of localised heating.
- Furthermore, the fillets of graphite cement may have enabled the current to take a path on the outer surface of the heating element heating only the outer ring of the monolith and leaving the channels relatively cooler, effect resulting in an inefficient heat transfer mechanism.

Following this, the resistojet rig was disassembled, and the fillets of graphite cement were removed. Having restored the resistojet rig to the original setup, the exit gas temperatures from the preliminary testing were once again obtained with similar voltage and current readings. The short-circuiting property of the thermocouple placed to measure monolith temperature was also verified, conducting the same test with and without this thermocouple in place.

Having revealed the inadequacy of the connections providing electrical power to the carbon monolith further testing with Xenon was deemed a waste of resources as it would not reveal any useful results, and thus experimentation was concluded until an improved monolith (with a higher resistance) could be obtained, and the thruster casing redesigned to compensate for the issues outlined above.

4.3. Discussion

Electrical efficiency of the heater assembly has been highlighted as an area of prime concern surrounding this technology. A future design iteration of the resistojet rig accommodating this type of heater technology must provide full electrical isolation of the heating element from any conductive element in the remainder of the thruster assembly that may drain power or provide an alternative current path.

The ability of the heating element to dissipate a greater amount of power without the need for high currents in excess of 10A is another concern. Figure 4.4. below predicts how much current would be required for an 800 °C temperature rise in various mass flow rates of nitrogen using a 5cm long carbon monolith having material resistances ranging from 0.1 – 1 Ω/cm. Figure 4.5. shows the same for various Xenon mass flow rates. These predictions assume that the heat transfer process to the gas is 50% efficient. Hence to alleviate the aforementioned concern, the heating element will have to undergo a manufacturing process that ensures it has a suitably high resistance of (0.5 – 0.75 Ω/cm) whilst being able to sustain high operating temperatures (800-1000 °C). Whether this can be achieved will be the subject of further research to be agreed with MAST.

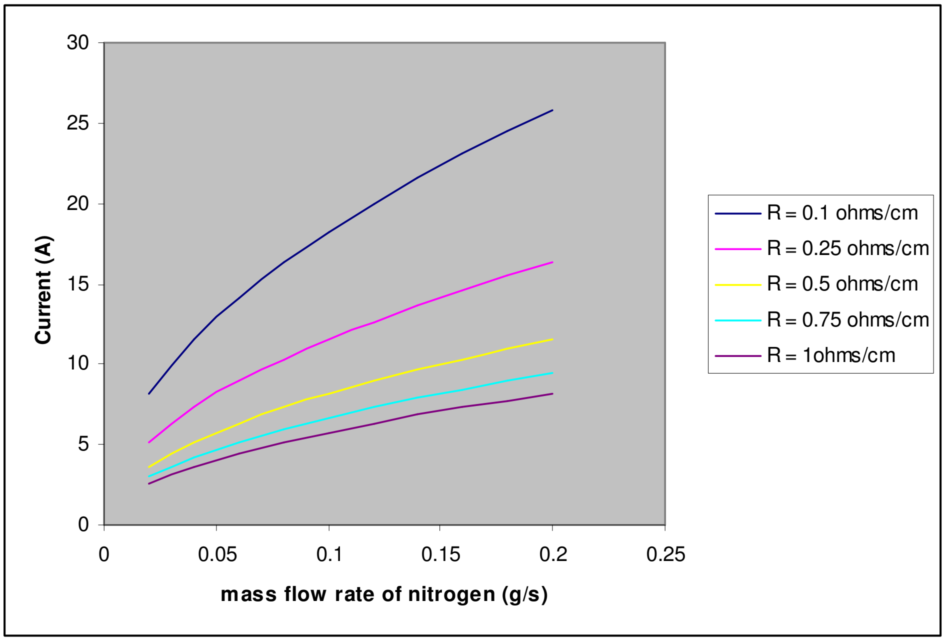


Figure 4.4. Current vs. nitrogen mass flow rate profile yielding an 800 °C temperature rise using a 5cm long monolith.

Additional MAST data has suggested that processing a monolith at 650°C should result in a resistance of 5Ω for a 50mm long monolith, which would enable considerable additional resistance heating for a lower current than the monolith tested at SSTL. This will limit operational temperature maximum to ~600°C, which in turn will limit Isp performance to the same as the current SSTL low power resistojet, i.e. between 45 and 50s with xenon propellant at ~10mN thrust and 30W input power. Further attempts to boost Isp will be considered when additional materials development has been performed which might reduce the negative correlation between the processing temperature (hence the operational temperature) and the final monolith resistance.

However the two other goals of the programme, improved electrical efficiency and reduced response time have shown a little more promise in this preliminary research exercise.

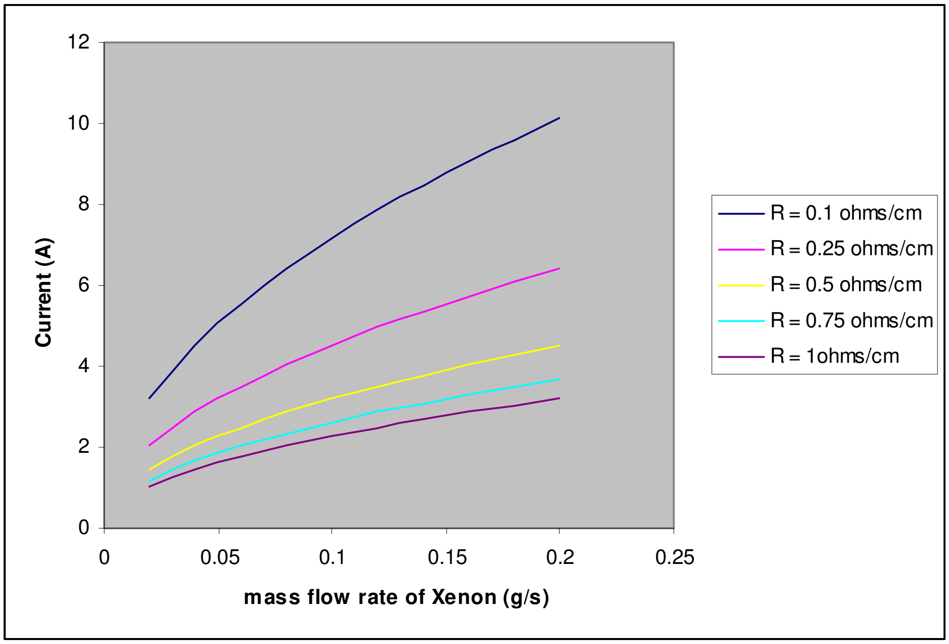


Figure 4.5. Current vs. Xenon mass flow rate profile yielding an 800 °C temperature rise using a 5cm long monolith.

A positive result from the test efforts was the fine transient performance of the heating element. It showed the potential to heat up gas to a steady maximum temperature in a short time of 30-60 seconds that appears to be independent of gas mass flow rate.

4.4. A brief note on thruster performance

The purpose of this section of the report is to illustrate what sort of thrust-performance a real thruster operating on high temperature nitrogen or xenon gas would yield.

Table 4.4. below shows two data points from experimental test cases performed on the low power resistojet tests with nitrogen and xenon at ESTEC (from AD-02 and AD-03). The table also shows ideal performance data calculated using the expressions in section 3.3.

From experimental measurements					Calculated using expressions in section 3.3.	
Input Power (W)	**Mass flow rate of gas (g/s)**	**Chamber temperature (°C)**	**Thrust (mN)**	**Specific impulse (s)**	**Thrust (mN)**	**Specific impulse (s)**
14.8	0.028 (nitrogen)	127	16	79.7	19	93
49.8	0.187 (xenon)	517	85.2	46.3	94	51.3

Table 4.4. Experimental and theoretical performance data for 2 data points from testing at ESTEC.

Comparison of the resistojet's performance obtained in practice (with a real nozzle) against the performance with an idealized nozzle expansion (discussed in section 3.3.) revealed that a real nozzle would expand the in-chamber gas with a chamber expansion efficiency of approximately 85% in the nitrogen test point case and 90% in the Xenon test point case.

Now, performance testing with nitrogen (at various chamber temperatures) at Polyflex on a DMC qualification thruster (discussed in AD-04) compared the performance of a thruster obtained in practice against that for an idealised case and this showed that a thruster would have a chamber to atmosphere expansion (or nozzle) efficiency that was lowest at room temperature and rose with the in-chamber gas temperature.

So applying the nozzle efficiencies reported above, to idealised cases of nitrogen and Xenon having similar mass flow rates as above, but, at higher chamber temperatures of 800 °C, would provide conservative estimates as to what the real performance of a new resistojet incorporating a heating element that could realise these gas temperatures would be. Table 4.5. below summarises these conservative predictions of performance.

	Specified		Calculated using expressions in section 3.3.		Predicted using a conservative chamber to atmosphere expansion efficiency	
Input Power (W)	**Mass flow rate of gas (g/s)**	**Chamber temperature (°C)**	**Thrust (mN)**	**Specific impulse (s)**	**Thrust (mN)**	**Specific impulse (s)**
Unknown	0.028 (nitrogen)	800	44.6	162.5	37.9	138
	0.187 (Xenon)	800	109	59.6	98.1	53.6

Table 4.5. Performance predictions for nitrogen and Xenon cases.

Hence the thruster performance specification outlined in table 2.2. could be met with relative ease if the current concerns with resistojet rig and monolith heating element can be resolved.

5. CONCLUSIONS

- Following on from the MAST testing of the carbon monolith heating element, a new monolith was procured, having been processed suitably to sustain operation at temperatures of 600°C or above to compete with the upper temperature limit of the current SSTL low power resistojet. However, the carbon monolith processing had not been suitably optimised to produce a heating element that could dissipate enough power to attain high operating temperatures whilst utilizing current inputs less than 10 A. Therefore, manufacturing processes will require suitable optimisation to ensure that a new heating element has a suitably high resistance of (0.5 – 0.75 Ω/cm) whilst being able to sustain high operating temperatures (800-1000 °C).
- Electrical efficiency of the heater assembly is the resistojet rig tested at SSTL was not satisfactory and resulted in unnecessary power dissipation across other elements of the resistojet thruster assembly. A future design iteration of the resistojet rig accommodating this type of heater technology must provide full electrical isolation of the heating element from any conductive element in the remainder of the thruster assembly that may drain power or provide alternative current paths.
- The testing at SSTL highlighted the above as two critical enabling features that have affected the performance realisation of this new heater technology. As a result, testing with Xenon gas was postponed until a second design iteration of the resistojet test rig can take place. It is intended to carry this out under internal SSTL R&D funds.
- A positive result from the test efforts was the fine transient performance of the heating element. It showed the potential to heat up gas to a steady maximum temperature in a short time (of 30-60 seconds) that appears to be independent of gas mass flow rate.
- A brief evaluation of the thrust-performance achievable with high temperature flows of Xenon and nitrogen has been performed using a conservative prediction technique. It is predicted that the required thruster performance specification (Isp target of 60s) could be met with relative ease if the current concerns with resistojet rig and monolith heating element can be resolved.

6. FURTHER WORK

6.1. Phase 1 - Improvements and extra tests planned under SSTL internal research & development funding

- MAST will be tasked to optimise their monolith manufacturing process and endeavour produce new heating element having a suitably high resistance (total resistance 4 - 5Ω) whilst being able to sustain high operating temperatures of at least 600°C.
- A design iteration on the resistojet rig accommodating the new heater technology will take place with requirements to provide full electrical isolation of the heating element from any conductive element in the remainder of the thruster assembly that may drain power or provide alternative current paths. This will also minimise thermal sinks, for example the current stainless steel nozzle.
- The postponed testing with Xenon gas will take place once the critical properties of the resistojet rig and heating element have been suitably rectified and the expected performance verified.
- The long term stability of the carbon monolith material after several heating / gas flow / cooling cycles has yet to be established. This will require a series of tests once the above issues have been addressed. A minimum lifetime target would be 500minutes of propellant flow time at temperature, which equates to 168 x 3 minute operating cycles at 30W input power. This target was derived from the AlSAT-1 low power resistojet in-orbit commissioning and initial mission operational experience.

A comprehensive heater performance evaluation report will be composed using the tests with the upgraded resistojet rig.

6.2. Phase 2 – Future work under unsecured funding to be agreed upon

- An optimised resistojet thruster is planned (i) using a PID controller to accurately control temperature and current requirement, (ii) incorporating an improved, stable resistance material suitable for operation >800°C with suitable resistance.
- Testing in pulse mode and determination of minimum impulse bit performance, for potential AOCS / precision pointing application.
- Explore carbon to SiC conversion for use in oxidising environments such as thermally induced decomposition of N_2O.
- Explore combining carbon with Ru catalyst for use as an NH_3 propellant decomposer.

APPENDIX A. PERFORMANCE TESTING WITH NITROGEN AT POLYFLEX (for reference)

From AD-04

At the same time as the DMC qualification thruster was manufactured another resistojet was procured for the BNSC Sector Challenge Programme. This was manufactured to identical geometry as the DMC unit. The only difference was that the heaters were rated at 50 Watt each. Polyflex performed functional testing on this unit with Nitrogen. Thrust and mass flow rate were measured in a vacuum vessel at their facility. The test equipment, procedure and results are presented in RD 2.4

Figure C.1 presents the results obtained from this test. The lower line is the best fit for the actual measured specific impulse. The dashed line is the best fit for the corrected specific impulse after the slight back pressure in the chamber has been taken account of. It can be seen that the corrected specific impulse is below the theoretical specific impulse calculated assuming a 100% efficient engine.

Resistojet - Temperature / ISP

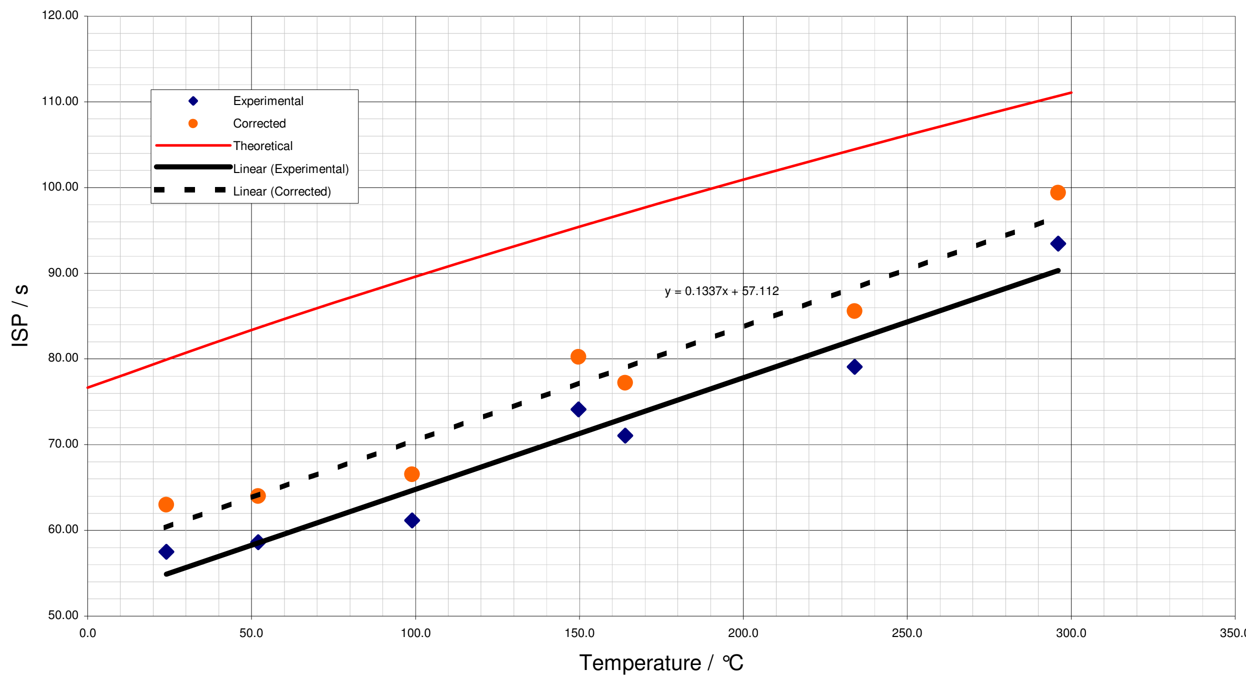


Table A.1 – theoretical and corrected measured specific impulse data

Temp / °C	Theoretical Isp / seconds	Corrected measured Isp / seconds	% efficiency
0	76.7	57.1	74.5%
50	83.4	63.8	76.5%
100	89.6	70.5	78.6%
150	95.4	77.2	80.9%
200	100.9	83.9	83.1%
250	106.1	90.5	85.3%
300	111.1	97.2	87.5%

Table A.1 shows that the thruster has an efficiency of around 75% at room temperature, rising to 87.5% at 300ºC.